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BOUNDARY-LAYER TRANSITION AT MACH 3.12 AS AFFECTED BY COOLING AND NOSE BLUNTING

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SUMMARY

An investigation was made to determine the combined effects of nose blunting and cooling on boundary-layer transition. Data are presented for both sharp and blunted cone-cylinder and parabolic-nosed - cylinder bodies at Reynolds numbers per foot up to 8×10^{6}.

Blunting the cone-cylinder model to a nose diameter of 3/16 inch (0.107 of max. body diam.) increased the transition Reynolds number over that obtained on the sharp model. The delay in transition with surface cooling was greater than that at equilibrium and is attributed to the increased stability of the boundary layer with cooling. These results at the lower temperature levels approached values predicted previously by theory. Blunting the nose of the parabolic-cylinder model to a 3/16-inch diameter (0.107 of max. body diam.) produced no increase in transition Reynolds number over that measured on the sharp-nosed model at all temperature levels.

On both the cone-cylinder and parabolic-cylinder models, moderate cooling resulted in an increase in the transition Reynolds number; extreme cooling, on the other hand, decreased the transition Reynolds number. This reversal effect indicates that the transition Reynolds number may not be increased indefinitely by cooling and that a limiting temperature ratio might exist below which the laminar boundary layer becomes less stable.

INTRODUCTION

In an investigation of boundary-layer transition on a hollow cylinder model (ref. 1), a significant delay in transition was obtained by slightly blunting the leading edge. The delay noted in reference 1 was attributed to the development of the boundary layer within a low unit Reynolds number region adjacent to the body surface (ref. 2). This region in the flow field results from the bow shock wave produced ahead of the blunted leading edge. Subsequently, the original investigation of reference 1 was extended to axisymmetric bodies (unpublished data). In this case, however, blunting the nose of a cone did not have as large a favorable effect as was experienced on the hollow cylinder.

The work in reference 1 was conducted under zero heat-transfer conditions. The present study considers the effect of blunting together with heat transfer on the cone-cylinder and parabolic-cylinder bodies reported in reference 3.

SYMBOLS

The following symbols are used in this report:

c_p	specific heat at constant pressure
h	local heat-transfer coefficient
Re	Reynolds number, $\frac{u_0}{\nu_0} x$
$Re_{cr,min}$	minimum critical Reynolds number
T	temperature
T'	stagnation temperature, $^{\circ}R$
t	time
u	velocity
x	axial distance
ν	kinematic viscosity
ρ	density
τ	skin thickness

Subscripts:

ad	adiabatic wall
b	model
t	transition
w	model wall
0	free stream ahead of shock wave

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APPARATUS AND PROCEDURE

Tests were conducted at a Mach number of 3.12 in the 1- by 1-foot supersonic tunnel at the NACA Lewis laboratory. The experimental setup, including model construction, tunnel mounting, instrumentation, and test procedure, was the same as that described in reference 3. The configurations used in that report were blunted to a nose diameter of 3/16 inch (0.107 of max. body diam.) for the tests discussed herein. Shown in figures 1(a) and (b) are the locations of the calibrated copper-constantan thermocouples for the sharp-tip models; figures 1(c) and (d) present the same information for the blunt-tip models. A typical model installation in the wind tunnel can be seen in figure 2. For each test condition, the models were precooled to a starting temperature ratio T_w/T_{ad} of 0.26, after which temperature histories were recorded as the configurations warmed up. Data were collected for Reynolds numbers per foot as high as 8×10^6.

Since the effects of heat conduction and radiation are shown to be negligible in reference 4, heat-transfer coefficients could be computed from the following simplified expression:

$$h = \frac{\rho_b c_{p,b} \tau \frac{dT_w}{dt}}{T_{ad} - T_w}$$

The manner in which the various quantities in this equation were evaluated is also described in reference 4. From a plot of heat-transfer coefficient against Reynolds number, transition was chosen as that point where the coefficient began to increase above the laminar value. In addition, transition in some instances was chosen directly from the oscillograph traces. Here, the increase in the rate of change of deflection is associated with the sudden increase of the heat-transfer coefficient. Both methods agreed very closely. It is felt that the selection of the transition location, as defined herein, was consistent to within 1/3 inch on the models.

RESULTS AND DISCUSSION

Cone-Cylinder Model

The experimental data for the cone-cylinder are shown in figure 3, where wall to adiabatic-wall temperature ratio is plotted against transition Reynolds number. The value of wall temperature in the preceding ratio represents the model temperature at the point of transition. Included in the figure are the results for both sharp-tip and blunt-tip configurations. It can be seen that cooling produced a large increase in the transition Reynolds number in both cases. In addition, it is apparent that blunting the tip caused a further delay in the onset of transition. On the average, with zero heat transfer ($T_w/T_{ad} = 1$) blunting the nose increased the transition Reynolds number from approximately 1.8×10^6 to a value of 2.7×10^6 or an increase of about 50 percent. With large amounts of cooling the increase in the transition Reynolds number, with bluntness, appears to have been greater. The 50-percent increase at equilibrium is comparable with recent results at the NACA Lewis laboratory (unpublished data) in which tests of hemispherical tips on a 10° cone produced at most a 30-percent increase in the length of laminar run on the body.

If it is assumed, for the moment, that the transition Reynolds number is unaffected by Mach number, then a predicted transition delay with bluntness could be obtained by the theory of reference 2. According to this reference, nose blunting lowers the local Mach number near the cone surface from 3.02 to 2.3; concurrently the unit Reynolds number is decreased by a factor of 2.17. The adiabatic-wall temperature changes by only $2\frac{1}{2}$ percent, which may be neglected. Under adiabatic-wall conditions, therefore, the theoretically predicted transition delay shows up as an increase in Re_t by a factor of 2.17. At the low-temperature end of the curve, the predicted transition delay factor is also 2.17. This theoretical variation can be seen in figure 3(a), where the solid curve is a fairing through the sharp-tip data and the dotted line is the predicted curve for the blunt configuration. As can be seen from the figure, the increase in transition associated with the change in unit Reynolds number was more nearly obtained at low temperatures than near adiabatic temperature.

However, wind-tunnel tests on insulated bodies (e.g., ref. 5) have consistently shown an increase in transition Reynolds number with decreasing Mach numbers below 3.5. From the data of reference 5, an additional transition delay by a factor of about 1.4 might be expected because of the decrease in Mach number from 3.02 to 2.3 caused by nose blunting. Finally, stability theory indicates that the temperature ratio for which the boundary layer becomes stable to very large Reynolds numbers increases because of this change in surface Mach number. The net result of these Mach number effects would be to further increase the difference between the predicted transition delays due to blunting and those obtained experimentally.

A plausible, though as yet unchecked, explanation for the increased effectiveness of bluntness at the low temperature ratios may be arrived at with the aid of stability theory. To begin with, it is assumed that the transition Reynolds number is related to the mimimum critical Reynolds number (that Reynolds number where disturbances in the laminar boundary layer are first amplified). Blunting causes the flow near the

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nose of the body to overexpand and subsequently to recompress. The adverse pressure gradient in the region of recompression has a tendency to destabilize the boundary layer, provided it occurs downstream of the minimum critical Reynolds number. Under conditions of zero heat transfer, $Re_{cr,min}$ is of the order of 3000 (ref. 6), while the start of the adverse pressure gradient has associated with it a Reynolds number ranging from 300,000 to 600,000. Consequently, for zero heat transfer, the adverse pressure gradient destabilizes the boundary layer and tends to promote transition. This factor partially counterbalances the favorable
4183 effect of blunting. Cooling, on the other hand, greatly increases $Re_{cr,min}$, even in the presence of an adverse pressure gradient (ref. 7). If $Re_{cr,min} > 600{,}000$, then the detrimental effect of the adverse gradient may be avoided; and more of the effect of blunting, as predicted in reference 2, can once again be realized. The results obtained on the cone-cylinder model tend to confirm this hypothesis.[1]

Parabolic-Cylinder Model

The results of the second configuration tested, a parabolic-nose cylinder, are presented in figure 3(b). As with the cone-cylinder model, there is a distinct effect of cooling on the location of transition, both with and without blunting. These data differ from the cone-cylinder results, however, in that blunting the parabolic model failed to produce an increase in the transition Reynolds number at any temperature level. It may be hypothesized that at adiabatic-wall conditions the adverse pressure gradient associated with the blunt parabola, which is more severe than that for the blunt cone-cylinder[2], exactly nullified the favorable effect of blunting. However, with cooling, blunting should have been more effective, as with the cone-cylinder; but no increase in the transition Reynolds number was noted. This fact, of course, casts additional doubt on the explanation for the increased effectiveness of bluntness with cooling proposed for the cone-cylinder model.

Shown in figure 4 is a comparison of the blunt cone-cylinder and sharp parabolic-cylinder data. Examination of these data indicates that

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[1]Recently, a variety of blunt-tip shapes have been tested on a cone at adiabatic-wall conditions. Although different magnitudes of adverse pressure gradient probably existed in the vicinity of these tips, no effect of tip shape on transition delay was noted. Consequently, the hypothesis that the tip adverse pressure gradient is affecting transition location may be questionable.

[2]Pressure distribution studies made by the authors on similar models indicate that the blunted parabolic model has a much larger adverse pressure gradient downstream of the tip than the conical model.

the experimental transition Reynolds numbers obtained from the blunt cone-cylinder almost coincide with the results obtained from the sharp parabolic model. Since blunting the parabolic model yields no further delay in transition, the more easily fabricated conical shape could be used without any great change in the location of transition. However, it should be pointed out that blunt bodies having favorable pressure gradients over their entire length might yield transition Reynolds numbers larger than those obtained in the present tests.

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Transition Reversal

Shown in figure 5(a) is the variation of transition Reynolds number on the sharp and blunt cone-cylinders at very low temperature ratios. If the data represented by each symbol are considered separately, then the data points at the lowest transition Reynolds numbers indicate the location of transition immediately after the start of the test. As the model warms up, the transition point moves downstream very swiftly and off the body. The increase in temperature necessary to produce this rapid movement of the transition point is sometimes rather insignificant. As the body continues to heat up, turbulent flow appears at the back end and moves forward with additional increases in temperature level. This forward movement is indicated by the solid curves discussed previously. At the time the sharp-tip cone results were first reported in reference 4, this reversal had not been detected since it occurs very early in the temperature history. A reexamination of these data revealed the presence of reversal. In the low-temperature range of the data points, some fluctuation is apparent in the variation of surface temperature with increasing time. This fluctuation is due to experimental scatter.

Similar results were observed on the sharp and blunted parabolic-cylinder model. Reversal data for these configurations may be seen on figure 5(b). In addition, unpublished data at the NACA Lewis laboratory reveal reversal in the location of transition accompanying extreme cooling on both sharp and blunt bodies having surface finishes ranging from 4 to 1250 microinches. With large roughness, the reversal occurs within the length of the body; while for smooth bodies, as tested herein, the reversal is surmised to occur downstream of the base. The possibility that frost formation on the models may have caused the indicated reversal of transition was considered. However, this possibility was rejected since reversal was obtained with and without a frost formation.

The reversal phenomenon just discussed indicates that the transition Reynolds number may not be increased indefinitely by cooling, as implied by stability theory. On the contrary, reducing the surface temperature below the level associated with the reversal point has a destabilizing influence on the boundary layer.

CONCLUDING REMARKS

Wind-tunnel tests were conducted on a cone-cylinder and a parabolic-nosed cylinder to determine the combined effects of nose blunting and cooling on boundary-layer transition. Rounding off the cone-cylinder nose to a diameter of 3/16 inch (0.107 of max. body diam.) resulted in an increase in transition Reynolds number. At very low temperature ratios the increase over the sharp-tip data was greater than that at the adiabatic-wall condition, and approached the value predicted in reference 2. Additional transition delays due to the reduction of Mach number by blunting were not realized in this investigation. The greater gain in transition Reynolds number at the lower temperature ratios is attributed to the possibility that the boundary-layer instability point may be downstream of the adverse pressure gradient at the blunt nose.

Blunting the nose of the parabolic model failed to produce any increase in transition Reynolds number over that obtained on the sharp model.

At low temperature ratios, a reversal was found in the trend of downstream transition movement with decreasing surface temperature. It appears that the transition Reynolds number cannot be increased indefinitely by cooling and that an optimum temperature ratio might exist below which the laminar boundary layer becomes less stable.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 18, 1956

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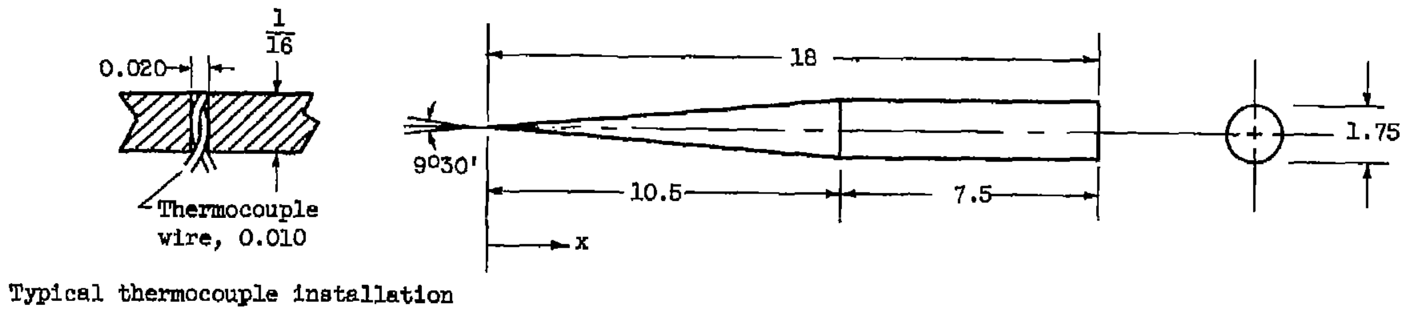
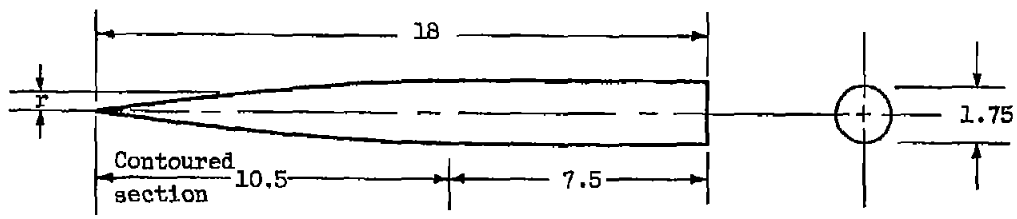


Thermocouple locations at axial distance x														
2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	10.62	11.50	12.50	13.62	14.75	16.00

(a) Sharp cone-cylinder.

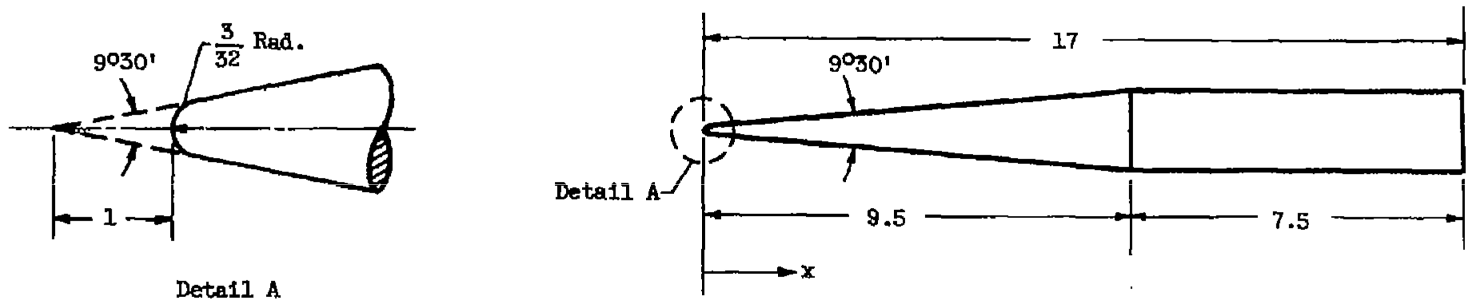


$$r = 3.5\left[\frac{x}{21} - \left(\frac{x}{21}\right)^2\right]$$

Thermocouple locations at axial distance x														
1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.5	14.0	16.0

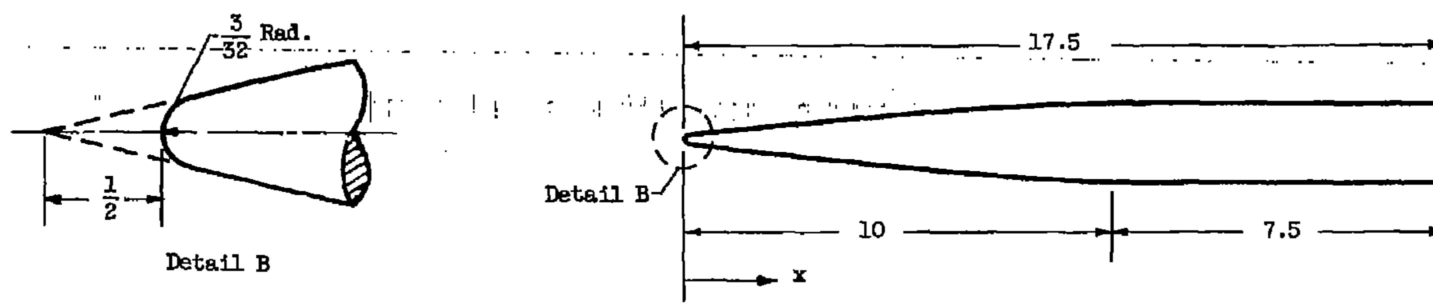
(b) Sharp parabolic-cylinder.

Figure 1. - Details of models and thermocouple locations. (All dimensions in inches.)



Thermocouple locations at axial distance x														
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	9.62	10.50	11.50	12.62	13.75	15.00

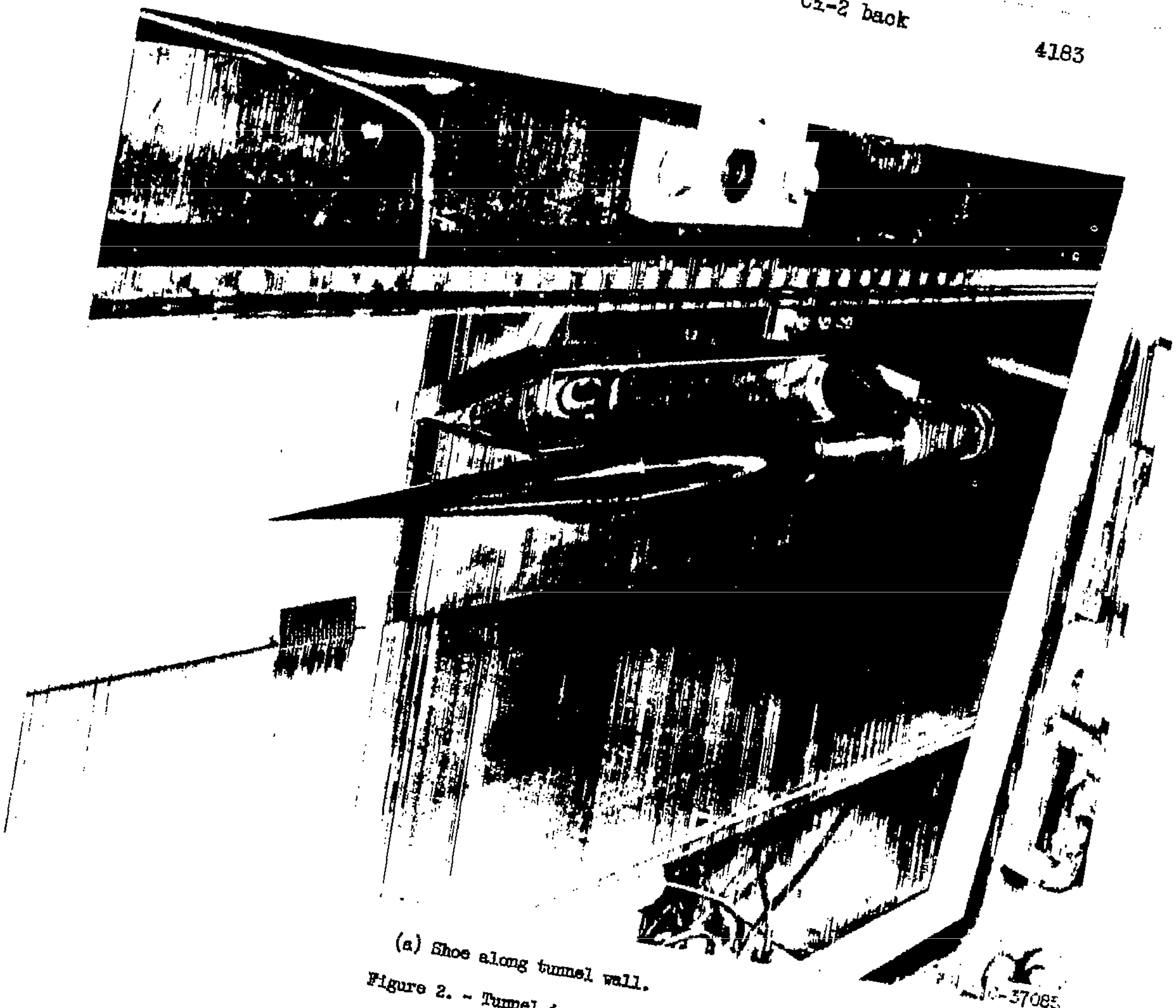
(c) Blunt cone-cylinder.



Thermocouple locations at axial distance x														
0.5	1.0	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	12.0	13.5	15.5

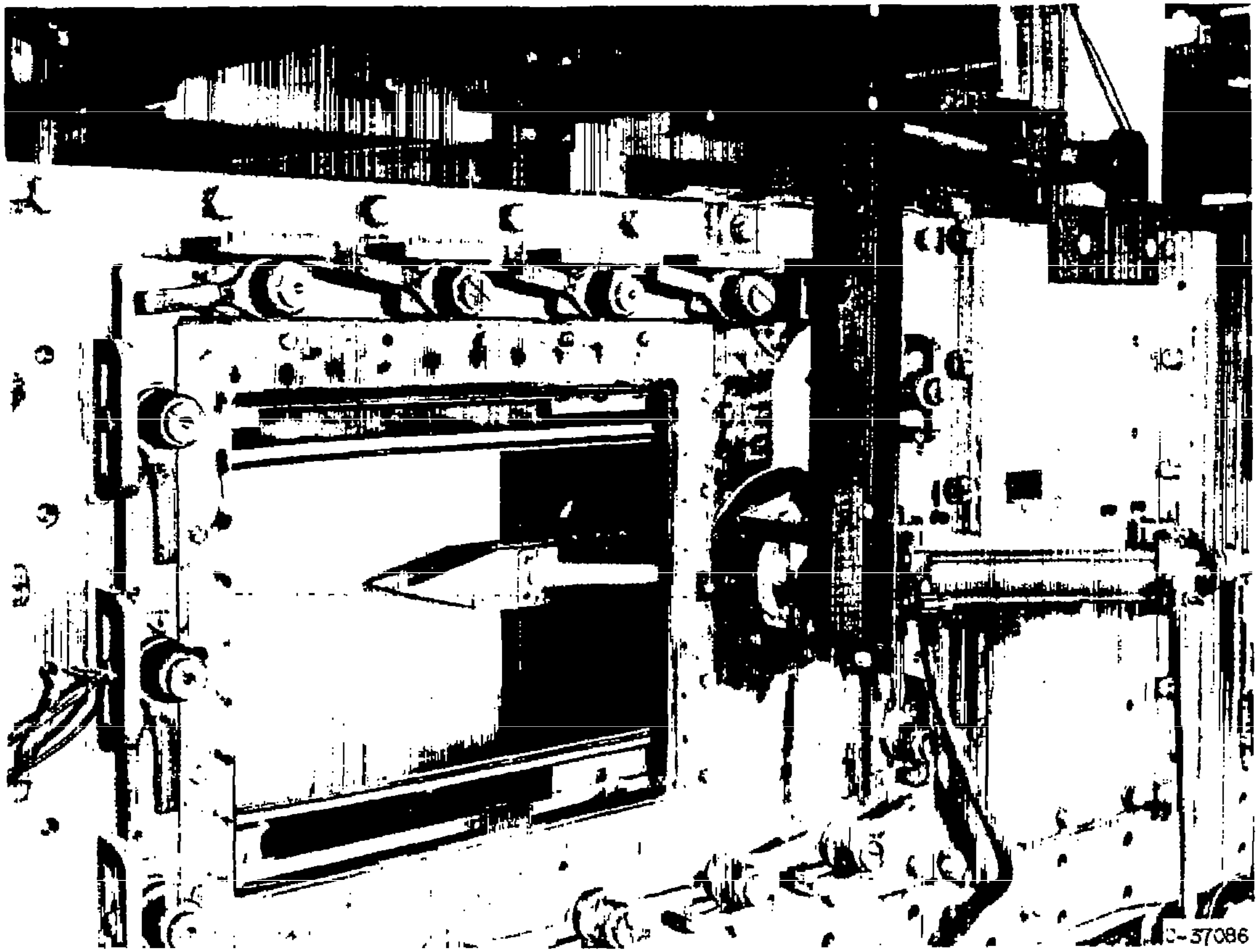
(d) Blunt parabolic-cylinder.

Figure 1. - Concluded. Details of models and thermocouple locations. (All dimensions in inches.)



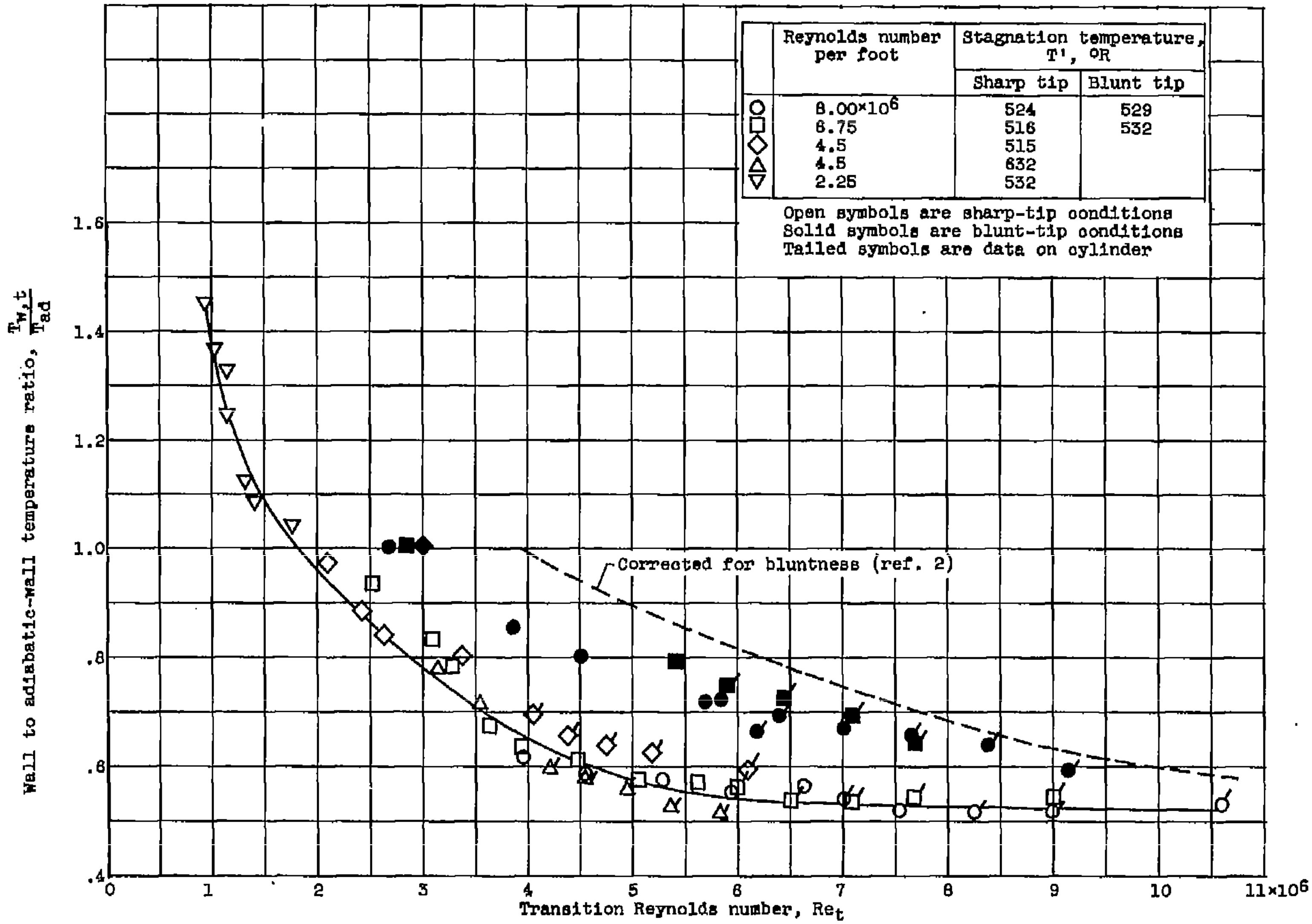
(a) Shoe along tunnel wall.

Figure 2. - Tunnel installation.



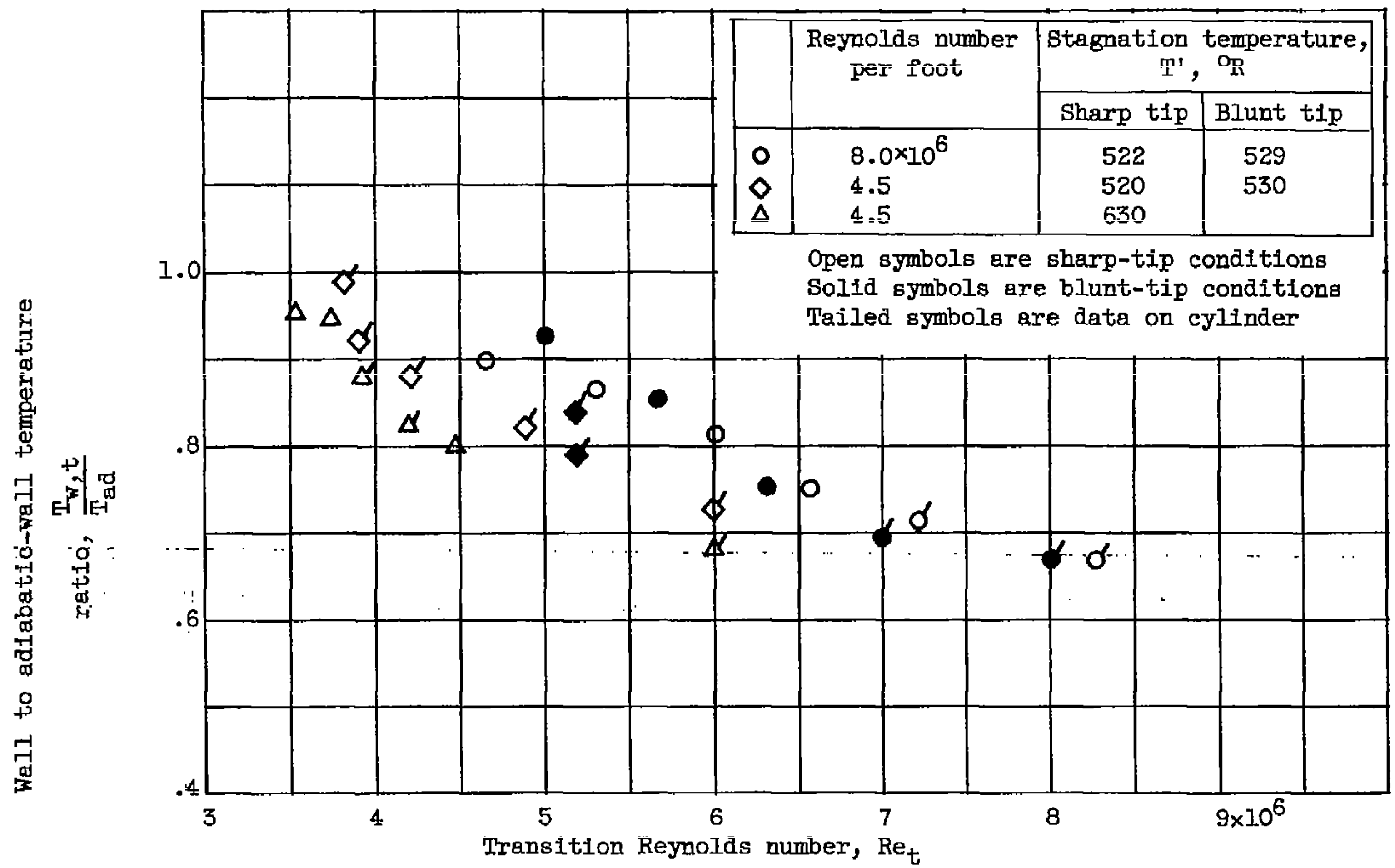
(b) Shoe in place.

Figure 2. - Concluded. Tunnel installation.



(a) Cone-cylinder model.

Figure 3. - Effect of cooling and tip blunting on boundary-layer transition.



(b) Parabolic-cylinder model.

Figure 3. - Concluded. Effect of cooling and tip blunting on boundary-layer transition.

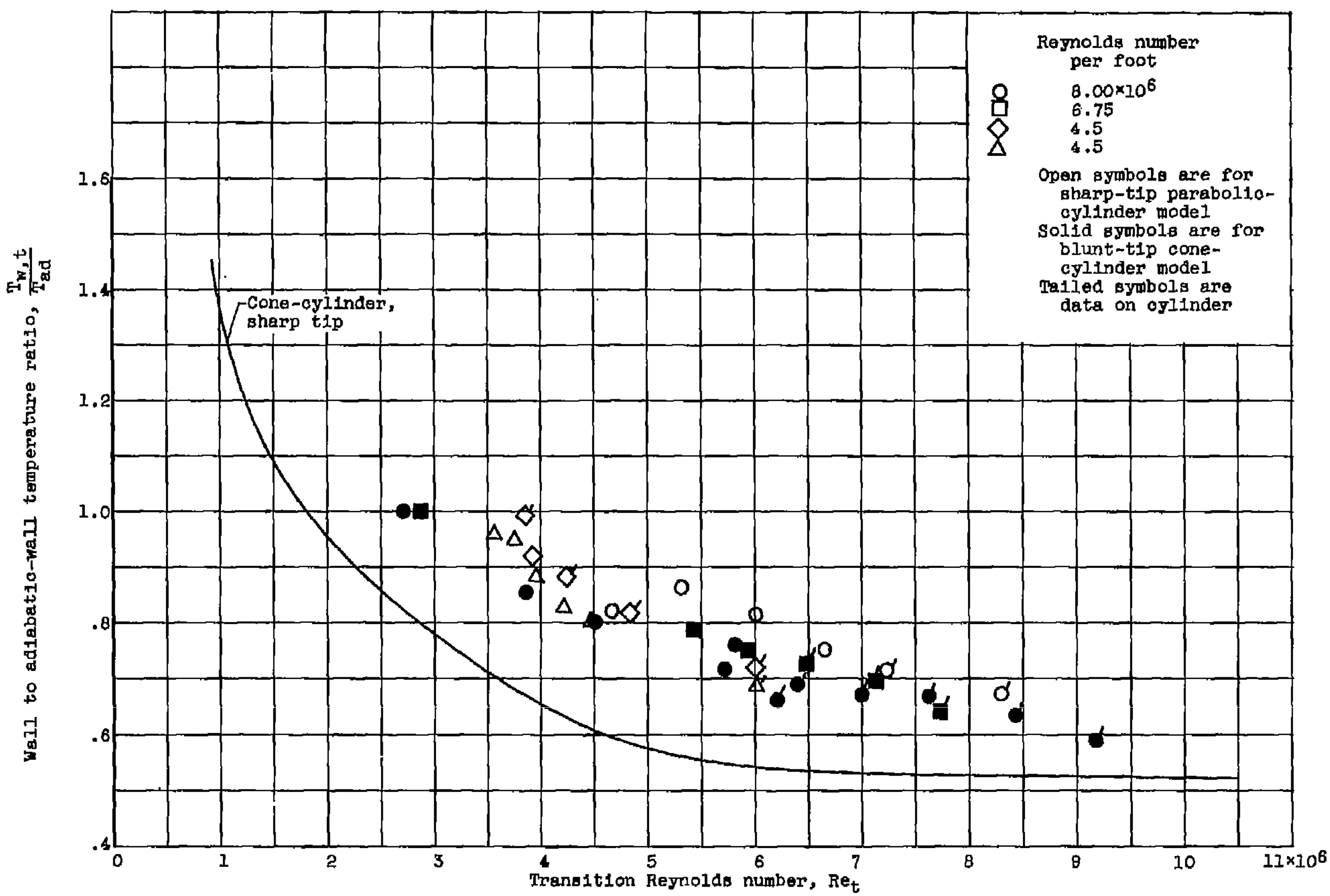
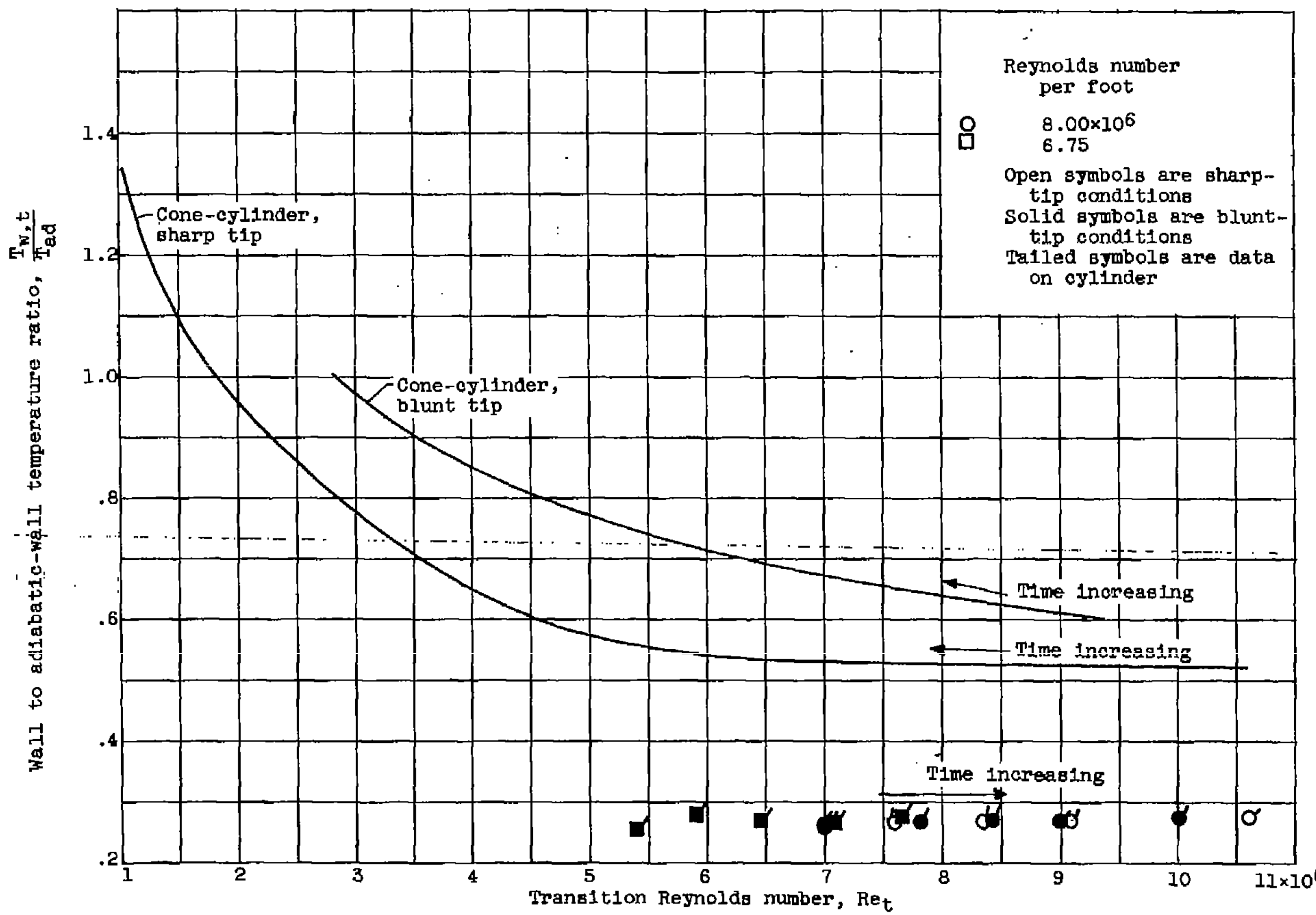
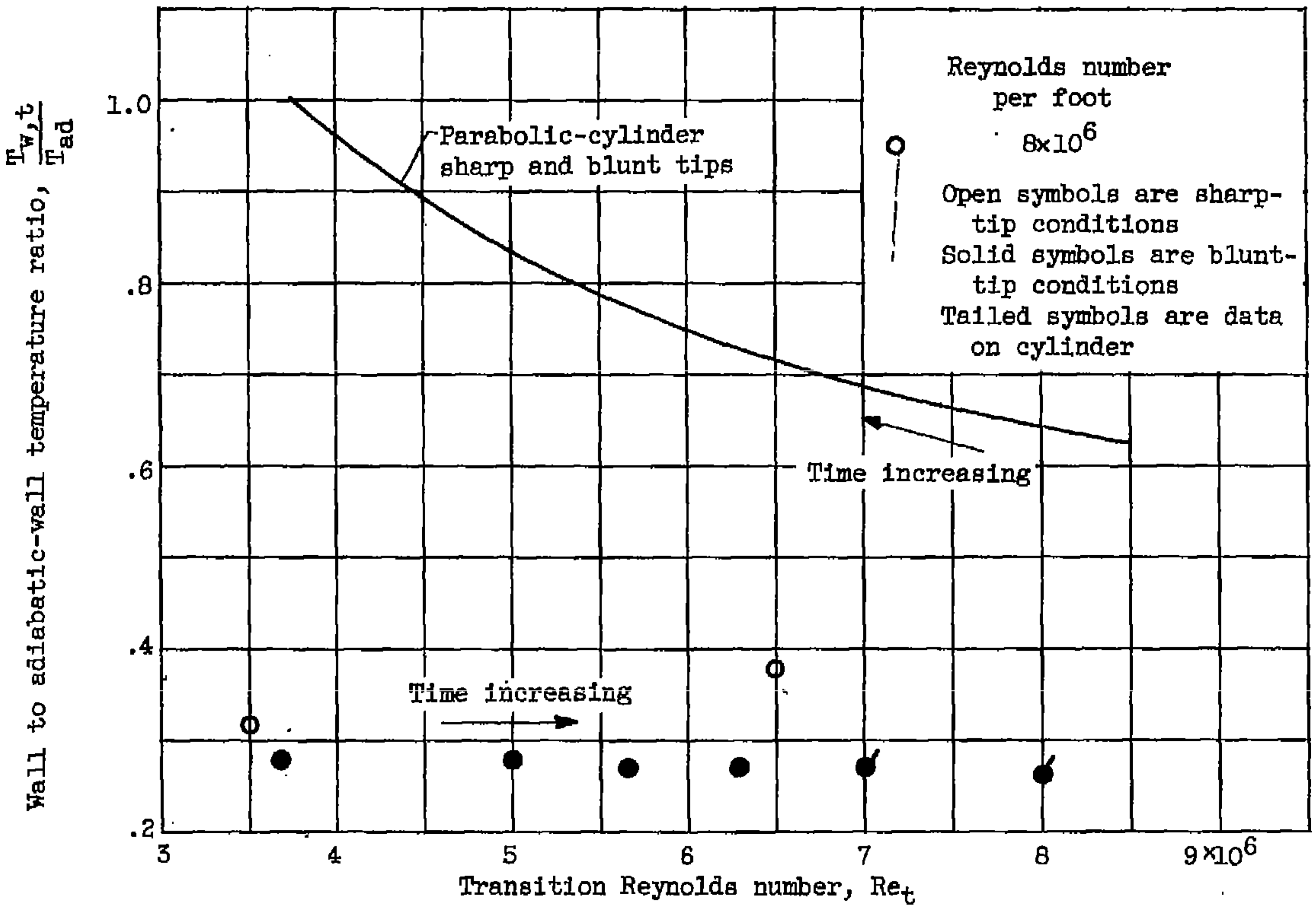


Figure 4. - Comparison of boundary-layer transition for blunt cone-cylinder and sharp parabolic-cylinder models.



(a) Cone-cylinder model.

Figure 5. - Effect of extreme cooling on boundary-layer transition.



(b) Parabolic-cylinder model.

Figure 5. - Concluded. Effect of extreme cooling on boundary-layer transition.

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